The Cassini INCA Sensor: Thermal Design, Analysis and Test

by

Edward I. Lin, Ronald T. Reeve, Glenn T. Tsuyuki and James W, Stultz
Jet Propulsion Laboratory
California Institute of Technology
Pasadena, California

Extended Abstract

The MIMI-INCA sensor (Magnetospheric IMaging Instrument - Ion and Neutral Camera) will be on board the Cassini spacecraft. to investigate the dynamics of the ion and neutral species in Saturn's magnetosphere and study the coupling between the magnetosphere and the ionosphere. The processes and results of thermal design, analysis and test for the INCA sensor are described in this paper, Attention is drawn to the manner in which the three processes interacted with one another, and the importance of the test in validating the design and analysis.

DESIGN. The INCA sensor is located on the upper shell structure assembly (USSA) of the Cassini spacecraft, with its close-up view shown in Fig. 1. The sensor consists of the upper and lower electronics housing, made of magnesium, which houses the electronics and detectors, and a collimator which is supported by, but isolated from, the electronics housing. The collimator fins are alternately charged, separated from each other, and supported on the ends by G-10 brackets. The energetic neutral or ion species from the hot plasma in Saturn's magnetosphere enter via the gaps between the fins, pass through the aperture which is located at the top of the upper housing, and are registered at the solid state detector matrix.

The sensor is mounted on the USSA by means of three aluminum bipeds. The collimator front is exposed to space, but the sides are blanketed, The Propulsion Module Subsystem (PMS) blanket envelops a cavity around INCA, and under this blanket the upper and lower electronics housing view the USSA, the MIMI main electronics, the hydrazine tank, and other neighboring subsystems. A sunshade extending from one of the collimator side plates provides protection against solar illumination during off-sun TCM's (Trajectory Correction Maneuvers).

The allowable flight temperature (AFT) requirements for the INCA sensor are: -20°C / -t- 35°C for min/max operational, and -25°C / -t- 50"C for min/max non-operational. These requirements are applicable to the bulk average of the electronics housing. No temperature limits or temperature-gradient requirements have been deemed necessary for the collimator due to the nature of the design and intended operations.

The INCA thermal design seeks to achieve a proper level of coupling between the instrument and the USSA. Conductive coupling is accomplished by the aluminum support structure which consists of three bipeds, the associated fittings and an interface plate. Radiative coupling takes place between the electronics housing and the surrounding cavity, which is enveloped by the PMS blanket. The neighboring subsystems inside the cavity, including the USSA, the MIMI main electronics, the hydrazine tank, the underside of the bus, etc.., present a generally warming influence on INCA. An earlier design utilized black paint on the electronics housing to maximize radiative coupling. However, the surface coating was later changed to DOW 15, a lower-emissivity finish (ϵ_{eff} = 0.13, as measured) which not only reduces the decontamination heater power substantially, but also lowers the instrument operating temperatures thereby attenuating detector noise.

Replacement, supplemental and decontaminate ion heaters are placed on the upper or lower electronics housing to keep the instrument within the allowable flight temperatures. The replacement heaters are sized to maintain the electronics housing above -25°C during the non-operating mode; the supplemental heaters are sized to maintain the housing above -20°C in the operating mode, including the sleep mode; and the decontamination heaters are sized to keep the housing temperature above + 20°C during decontamination.

ANALYSIS. The SINDA model is based on a reduced model constructed for the sensor proper, and includes a support structure model and various boundary condition representations obtained from pertinent neighboring subsystems. The model is simple yet contains sufficient details for the intended purpose of calculating bulk temperatures, Some TRASYS models of the collimator fins were also constructed to calculate the effective emissivity for the collimator that was subsequently incorporated into the reduced SINDA model.

As boundary conditions, the USSA temperature and the neighboring subsystems temperatures have an important effect on INCA's thermal state. The neighboring subsystems under the PMS blanket have been treated as a cavity effective sink, and both the USSA (conductive boundary) and the cavity effective sink temperatures have been provided from predictions using the spacecraft central body model. The overall thermal conductance of the biped support structure has been calculated considering all six struts, the fittings, and the various contact resistances at the bolted and bonded joints. Due to uncertainties associated with contact resistances and approximations of fittings' geometries, a sensitivity range for the overall thermal conductance is also estimated.

Analyses conducted include steady-slate calculations for worst-case hot and cold, and nominal hot and cold conditions; heater sizing and heater power sensitivity calculations; sensitivity studies varying the overall thermal conductance between INCA and the USSA, the cavity effective sink temperature, the high-emissivity black paint vs. the low-emissivity DOW 15 coating, and some key boundary conditions. The results are presented in Table 1.

Predictions for the lower electronics housing temperature indicate comfortable margins (greater than 11°C) for both worst-case hot and worst-case cold conditions. A heat flow diagram for the worst-case hot analysis (Case A 1) is presented in Fig. 2. Aside from the collimator-to-space heat path, major heat flows occur between the instrument electronics housing and the USSA, as well as the cavity. For heater sizing and heater power sensitivity, all runs were made under worst-case cold conditions. A decontamination heater size of 10W is required to maintain the electronics housing above 20°C. Although no replacement and supplemental heaters are required according to Case B1, these runs provide an insight into how the electronics housing temperature varies in response to heater power (roughly 3°C/W), and will be useful for comparison with test data.

The overall thermal conductance between 1 NCA and USSA includes uncertainty in the values of thermal conductivity and contact resistance, and in the estimation of area and length along the heat flow path. The thermal-conductance sensitivity studies show greater sensitivity in the cold case than in the hot case, but the lower electronics housing temperature varies no more than 3°C from nominal within the uncertainty band in all cases. The sensitivity study with regard to the cavity effective sink temperature indicates that for every 10"C variation in the cavity temperature, the lower electronics housing temperature will be affected by about 3°C (Fig. 3).

An earlier INCA design was baselined with a black paint on the housing to maximize the coupling between INCA and the spacecraft. However, subsequent analysis considering revisions in the key boundary temperatures and in the AFT requirements revealed that DOW 15 ($\epsilon = 0.13$) is advantageous to black paint ($\epsilon = 0.87$). The lower emissivity coating reduces decontamination heater power by 10 W, and reduces the instrument operating temperatures by 4 or 5°C thereby damping the detector noise. Cases E1-E5 in Table 1 are to be contrasted with Cases Al -A4 and B6. This comparison is depicted in Figure 4 by the bar in the middle and the bar on the right. 'l'he bar on the left recapitulates the pre-1994 design and analysis results to give a historical background. The current design is represented by the bar on the right, which illustrates that the design is within the AFT limits with comfortable margins.

Transient analyses include the case of trajectory correction maneuver (TCM) with the spacecraft off the normal sun-pointing configuration at 0.6 AU (2.'/ suns exposure), the case of loss of sun knowledge fault for a hypothesized 6-min duration, and a post-launch cooldown simulation. The TCM transient simulation at 0.61 AU starts with the worst-case hot initial conditions. The 2.7-sun irradiance is imparted on the side of the collimator which is protected by the sunshade. The event is projected to last 30 rein, but the simulation was run for 1 hr. The results show that the sunlit MI,1 outer layer temperature rises to 186°C, the sun-side collimator side plate temperature rises from 6.4°C to 39.6°C, and the lower electronics housing temperature increases from 22 .2°C to only 23 .7°C. All temperatures are within AFT requirements and material limits.

The simulation for the loss-of-sun-knowledge fault at 0.61 AU (closest solar approach for the design) also starts with the worst-case hot initial conditions. The 2.7 suns illuminate the collimator head-on beaming down the instrument bores ight. The simulation results show that the lower electronics housing temperature is hardly raised during the first 6 min. which is the postulated event duration. The collimator temperature is predicted to increase from -91.1 'C to -80.9°C after 6 min. (and to 3.7°C after 1 hr.) However, it was recognized that these transient predictions based on a lumped-parameter one-node treatment for the collimator are not meaningful. In reality, the gold-plated thin fins individually will have fast response to the transient event, and the fin temperatures were expected to rise to a very high level as demonstrated later by the thermal development test. For the transient response during post-launch cooldown, the simulation starts with a uniform temperature of 15°C for the instrument and spacecraft, all power being turned off. The event is projected to last no longer than 2 hours but the simulation was run for an additional hour. The results indicate that the lower electronics housing cools to 6. 1°C after 2 hours, well within the AFT limits.

VERIFICATION TEST. The INCA sensor test article is shown in Fig. 5 before the installation of the PMS blanket which wrapped around the electronic housing to create a simulated PMS cavity around the sensor. The thermal development test accomplished all the test objectives, 'l'he INCA thermal design was verified to be sound and robust, capable of satisfying all the thermal requirements under the worst-case conditions with comfortable margins. The test concluded that the replacement and supplemental heaters can be eliminated (which were initially allocated 10.9 W and 7.0 W, respectively), and that the decontamination heater power can be reduced (from the initial 18.75 W to 15.0 W). Conservative, extended simulations of the post-launch cool-down, the off-sun TCM and the loss-of-sun-knowledge fault conditions at 0,61 AU revealed no problems. The replacement of black paint by the DOW 15 coating on the electronics housing was proven beneficial, and transient data collected for the collimator fins and aperture foil provide valuable insight into their thermal behavior under extreme conditions. Some key test results are described as follows:

Figure 6 summarizes the steady-state temperatures obtained from the test for the lower electronics housing. Data points A through E are derived from the following test conditions:

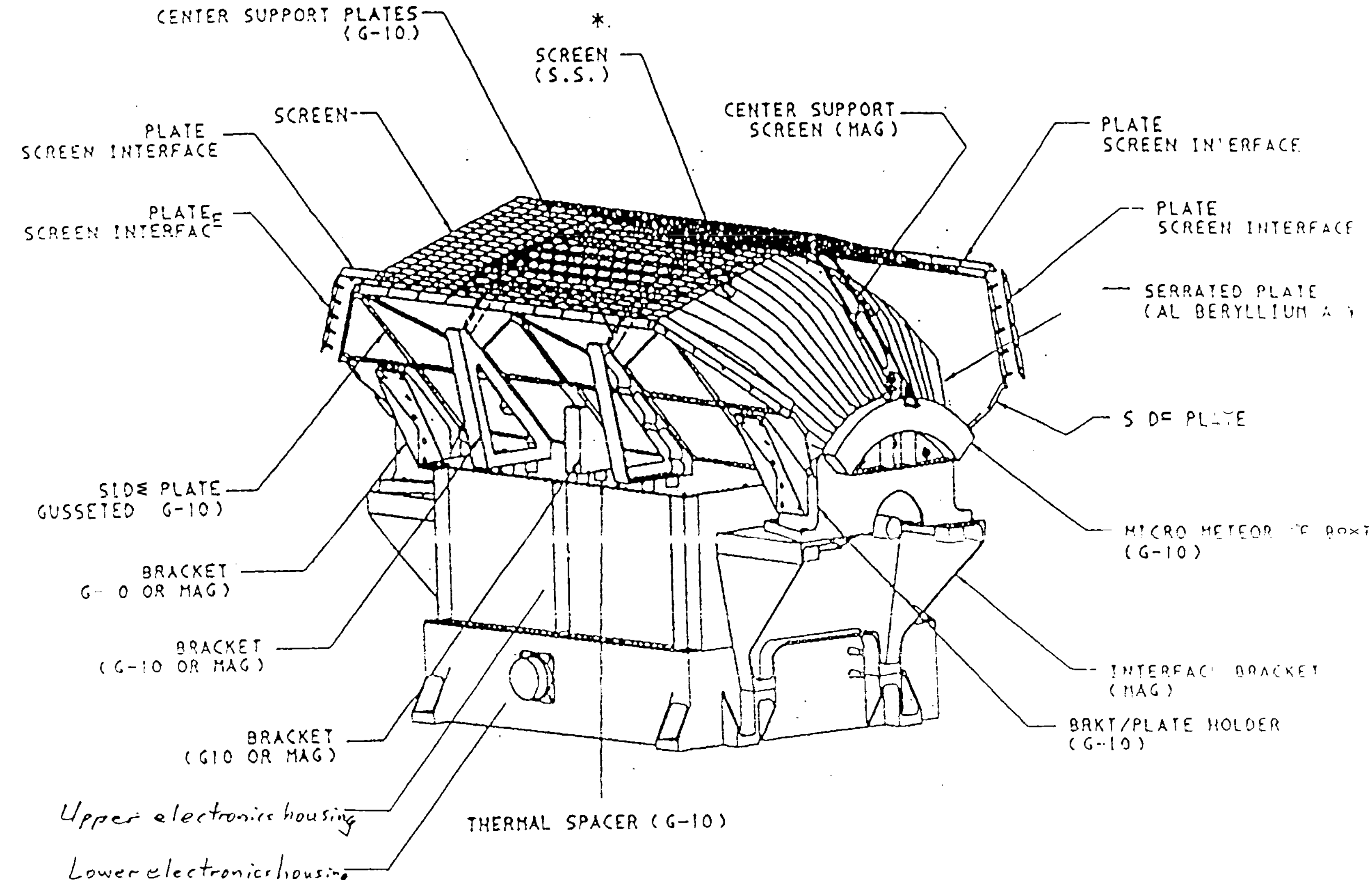
- A: Worst-case hot (INCA operating at 3.13 W, hot USSA at 32.2°C)
- B: Worst-case cold (INCA non-operating, cold USSA at 8.3°C)
- C: "Replacement heater sizing" (INCA non-operating, replacement heater at 2.53 W, cold USSA at 10. 1°C)
- D: "Decontamination heater sizing" (INCA ~]on-operating, decontamination heater at 13.5 W, cold USSA at 9.6°C)
- E: Hot sensitivity (INCA operating at 3.13 W, hypothetically hot USSA at 46.0°C)
- F: Cold sensitivity (INCA non-operating, hypothetically cold USSA at 1.2°C)

The results are presented in terms of the average lower electronics housing temperature, the average upper electronics housing temperature being typically 1.3 to 2.3°C cooler, A comparison of these test results and the AFT's indicates comfortable design margins both on the hot and cold sides. The worst hot case result (Data point A) indicates a 25°C margin, and the worst cold case result (Data point B) indicates a margin of 80(,

Data point B shows that the thermal design is viable for the worst-case cold conditions even without replacement and supplemental heaters. Data point C indicates that the application of 2.53 W of heater power will increase the lower electronics housing temperature by 7°C. Data point F shows that even if the USSA temperature dropped down to an unrealistically low 1.2°C, the lower electronics temperature was still 2°C above the minimum non-operating AFT, Noting that the warming effects of the surrounding subsystems (e.g., RSP, MIMI main electronics, etc.) was absent from the small simulated PMS cavity, and that the three test bipeds were somewhat cold-biased in their deviation from the flight configuration, it is clear that these non-operating cold-case tests point to the conclusion that replacement and supplemental heaters are unnecessary. "l'his corroborates with the analytical predictions. In fact, the last two observations (i. e., cold-biased bipeds and absence of the surrounding warm instruments) probably account for the fact that the test results are lower than the analytical predictions by about 8°C in the cold case and by about 11°C in the hot case. Also, data points 1 : and A show that $dT_{INCA}/dT_{USSA} \approx 12^{\circ}C/14^{\circ}C$, and data points B and F show that $dT_{INCA}/dT_{USSA} \approx 5^{\circ}C/7^{\circ}C$, indicating a high INCA sensitivity to the USSA temperature. Data point D (Fig. 6) indicates that a 13.5 W heater is almost sufficient for decontamination purposes. With a little extrapolation, it is evident that a 15 W decontamination heater is sufficient to keep the electronics housing above the desired 20°C during decontamination.

The transient test phases covered the post-launch cooldown, the spacecraft off-sun TCM, and the loss-of-sun-knowledge fault simulation. The test conditions were conservative, and all results indicate that the AFT requirements are satisfied. More details will be given in the paper, one example being Fig. 7, which presents the aperture foil temperature transients occurring during a 2,7-sun exposure, More will also be said about how the design, analysis and test processes interacted with one another. The verification test ascertained that the design and analysis that have been performed are adequate, and that the 1 NCA sensor should be able to meet all thermal requirements during the system-level thermal vacuum test, and throughout Cassini's mission to Saturn.

Hardware Description (cont'd)



* SCREEN OMITTED IN SOME AREAS FOR CLARITY.

Fig. 1 The NCA Sensor

Table I. MIMI-INCA Analysis Results

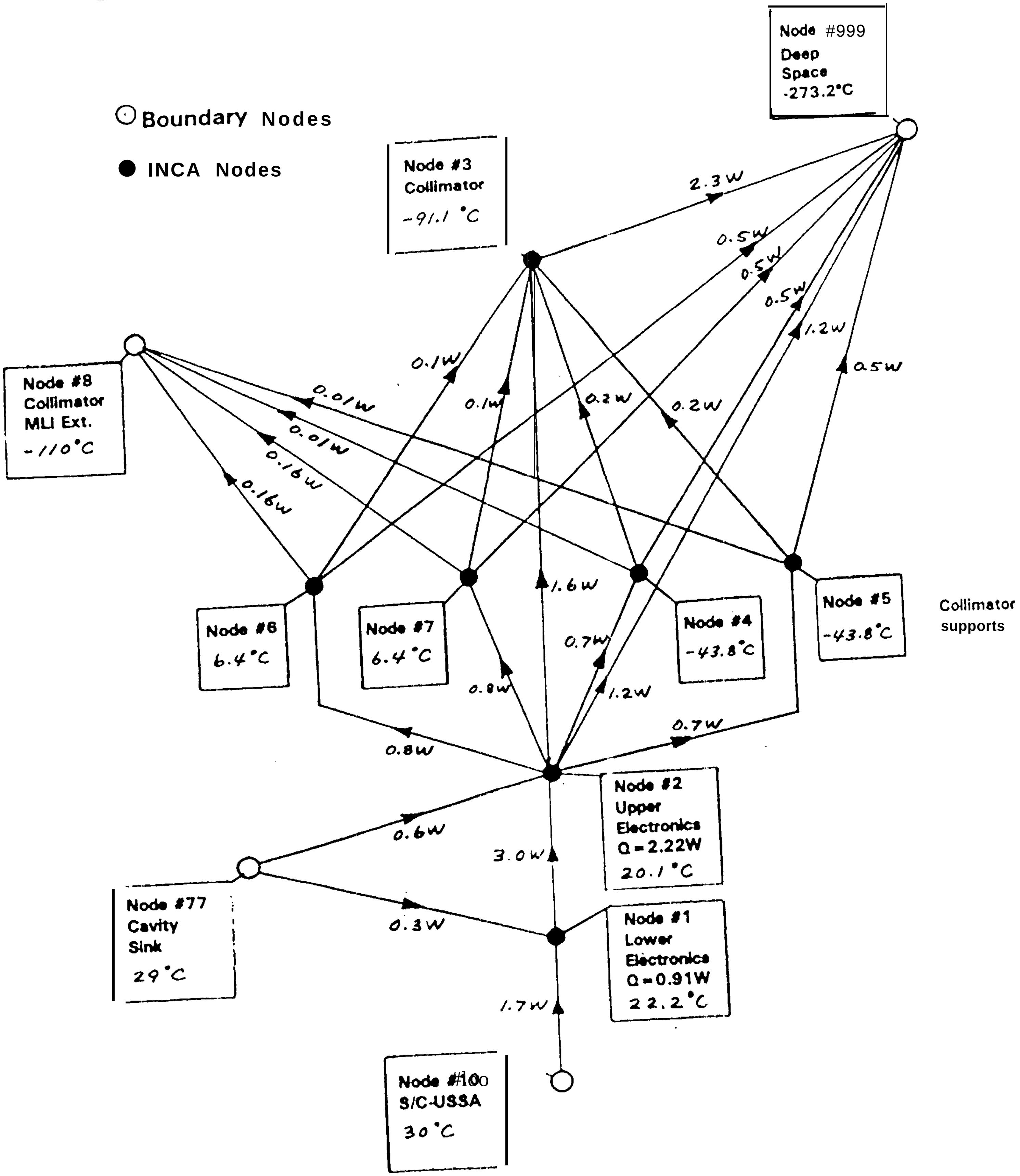
Run case	Case Conditions	Parameters: #100 USSA T (C)	#77 Cavity T (C)	#8 MLI-O T (C)	G(1-sc) (W/C)	MLI cff. E	Electr. Hous'g E	Oper. Power (W)	Heater Power (W)	Results: T1 (C)	T2 (C)	T3 (C)	T4,T5 (C)	T6,T7 (C)	Remarks
	Worst-Case Hot and Cold; Nominal Hot and Cold														
A1	Worst-Case Hot	30	29	-110	0.224	0.01	0.13	3.13	0	22.2	20.1	-91.1	-43.8	6.4	min/max op AFT
A2	Worst-Case cold	10	8	-130	0.139	0.04	0.13	0		-9.5	-11.9	[illegible]	[illegible]	[illegible]	are -20/+ 35 C;
A3	Nominal hot	25	23	-120	0.167	0.025	0.13	3.13		15.1	13.2	-95.3	-47.9	-2	min/max non op AFT
A4	Nominal cold	15	12	-120	0.167	0.025	0.13	[illegible]		6.7	4.8	-100.1	-52.2	-9.2	are -25/+ 50 C
	Heater Sizing and Heater Power Sensitivity														
B1	Worst-Case cold	10	8	-130	0.139	0.04	0.13	0		-9.5	-11.9	-109.8	-61.6	-25.3	
B2	Replacement Heater							0	2W@#2	-2.8	-4.4	-105.6	-57.7	-19.3	″
B3	Supplemental Heater							2.22	1W@#2	1.1	0	-103.1	-55.4	-15.7	
B4	Heater Power Sensitivity							0	4W@#2	3.5	2.8	-101.5	-53.9	-13.5	
B5	Heater Power Sensitivity							0	8W@#2	15.6	16A	-93.9	-47.1	-2.9	
B6	Decontamination Htr.							0	10W@2	21.3	22.9	-90.3	-43.9	2.1	
	Sensitivity Study - Overall Thermal Conductance Between INCA and USSA														
C1	Hot	30	29	-110	0.224	0.01	0.13	3.13	0	22.2	20.1	-91.1	-43.8	6.4	
C2	Hot				0.167					20.9	18.9	-91.8	-44.4	5.4	
C3	Hot				0.139					20.1	18.2	-92.2	-44.7	4.8	
C4	Cold	10	8	-130	0.139	0.04	0.13	0		-9.5	[illegible]	[illegible]	-61.6	-25.3	
C5	Cold				0.167					-7.7	-10.2	-108.9	-60.7	-24	
C6	Cold				0.224					-4.9	-7.7	-107.4	-59.3	-21.9	
	Sensitivity Study - Cavity Effective Sink Temperature														
D1	Hot	30	39	-110	0.224	0.01	0.13	3.13		25.4	23.4	-89.2	-42.1	9.2	
D2	Hot		29							22.2	20.1	-91.1	-43.8	6.4	
D3	Hot		19							19.4	17	-92.8	-45.3	3.8	
D4	Cold	10	20	-130	0.139	0.04	0.13	0		-5	-7.3	-107.2	-59.1	-21.6	
D5	Cold		8							-9.5	-11.9	-109.8	-61.6	-25.3	
D6	Cold		-15							-16.8	-19.6	-114.1	-65.7	-31.6	
	Black Paint on Electronics Housing (Instead of DOW 15)														
E1	Worst-Case Hot	30	29	-110	0.224	0.01	0.87	3.13		27	25.4	-88.1	-41.1	10.8	
E2	Worst-Case Cold	10	8	-130	0.139	0.04	0.87	0		2.6	0.8	-102.6	-54.9	-15.1	
E3	Nominal Hot	25	23	-120	0.167	0.025	0.87	3.13		20.9	19.3	-91.9	-44.9	2.4	
E4	Nominal Cold	15	12	-120	0.167	0.025	0.87	3.13		10.6	9.1	-97.7	-49.9	-5.8	
E5	Decontamination Htr.	10	8	-130	0.139	0.04	0.87	0	20W	21.2	25.1	-89.1	-42.8	3.7	
	Nominal Case Predicts (Varying USSA & Cavity Temperatures)														
F1	Hot	30	29	-120	0.15	0.025	0.13	3.13	0	19.3	17.1	-93.1	-45.9	0.7	
F2	Hot	25	23					3.13		14.8	12.8	-95.6	-48.1	-2.8	
F3	Cold	15	12					3.13		6.2	4.4	-100.3	-52.4	-9.6	
F4	Cold	10	8					0		-7.8	-10.2	-108.5	-60	-21.6	

Notes:

A blank parameter entry assumes the same value as the one immediately above

~~Figure 6~~

Fig. 2 Heat Flow Diagram: Worst Case Hot



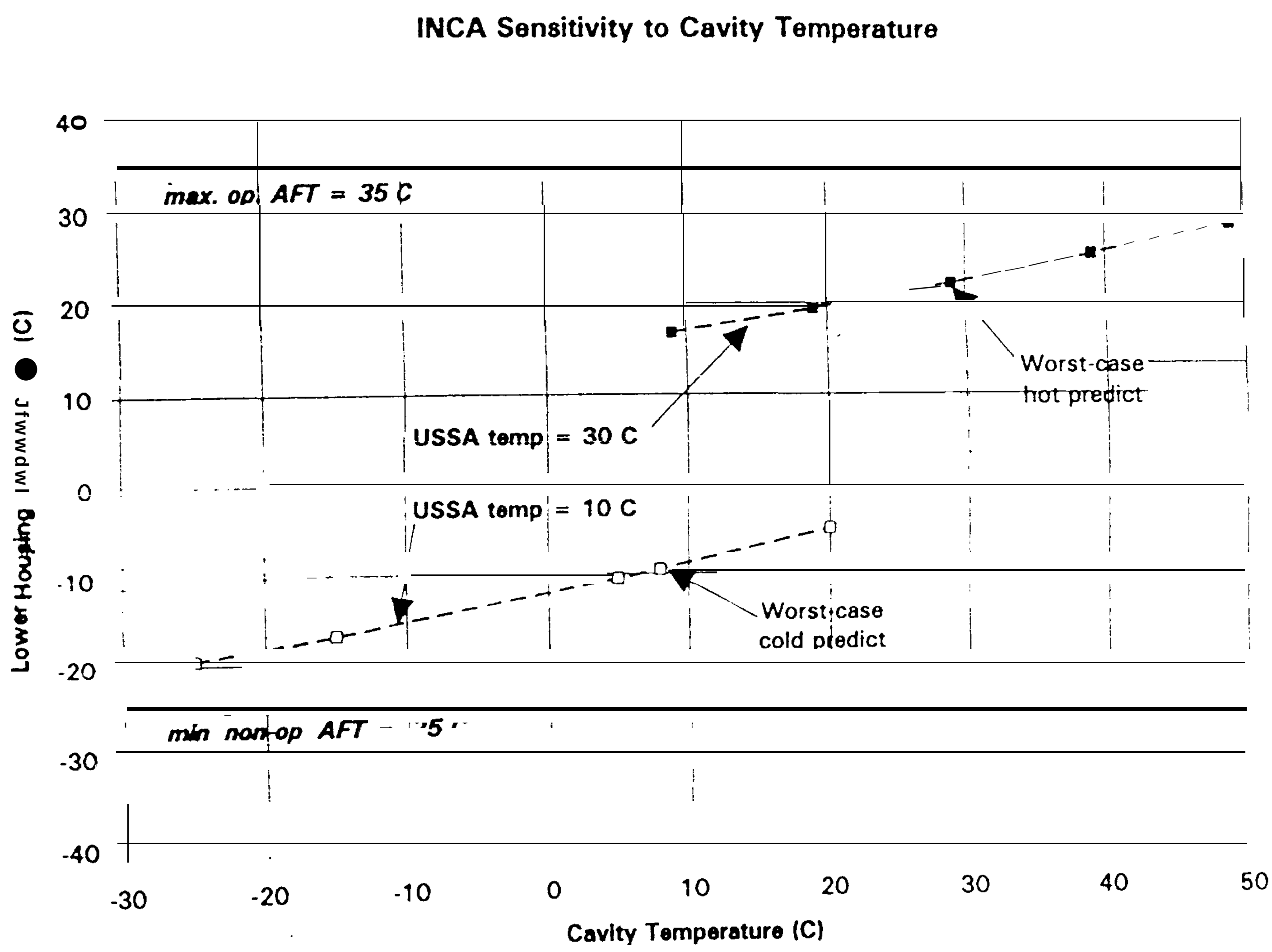
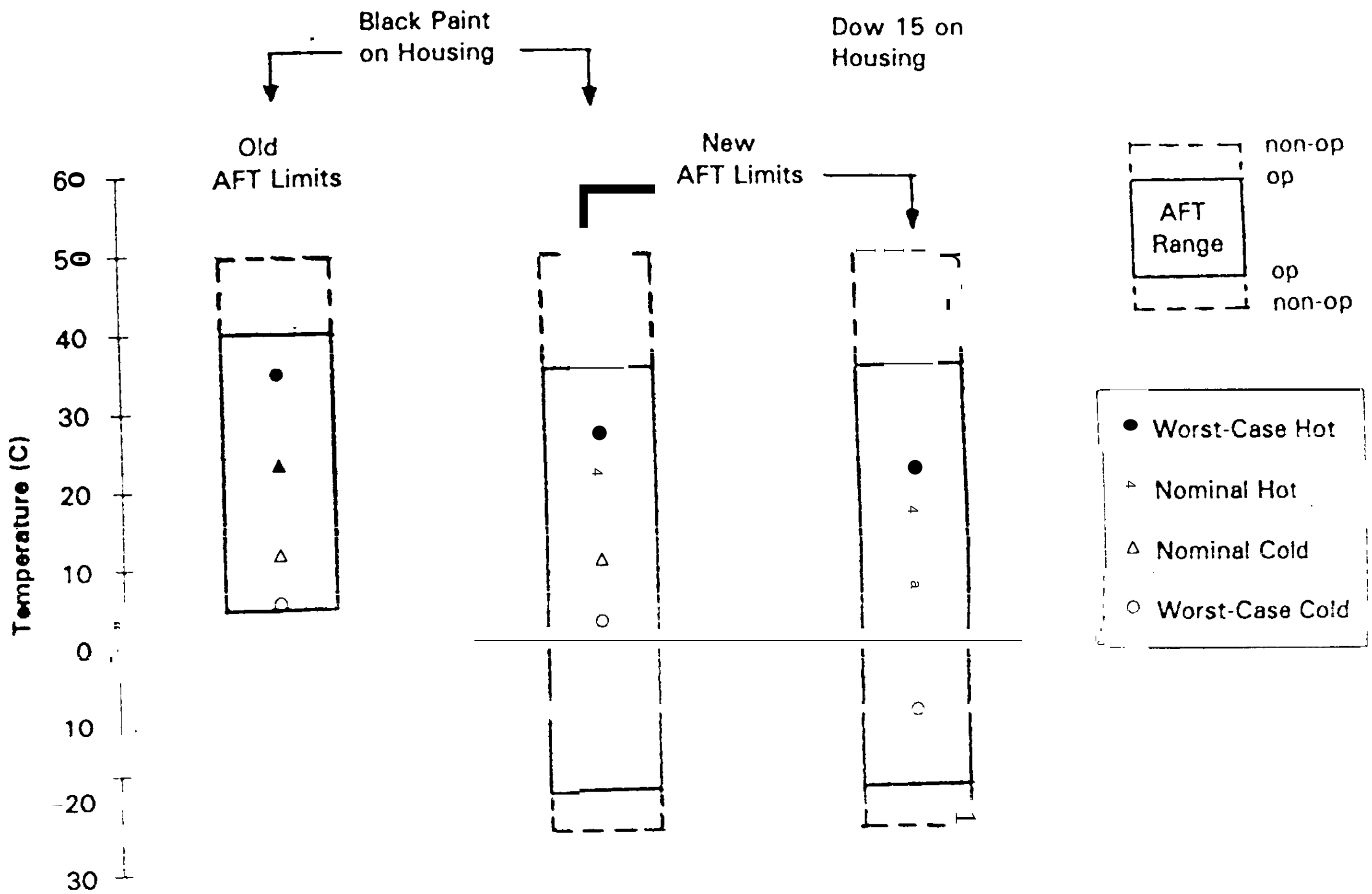


Figure 10 INCA Sensitivity to Cavity Effective Sink Temperature

3

INCA14A.XLC



R Heater	6.0 W	0.0 W	0.0 ω
Supplemental Heater	3.8 W	0.0 W	0.0ω
Decontamination Heater	23 ω	20 W	0 ω

Figure 4 INCA Lower Electronics Housing Temperature -- Nominal and Worst-Case

INCA_BAR.XLS

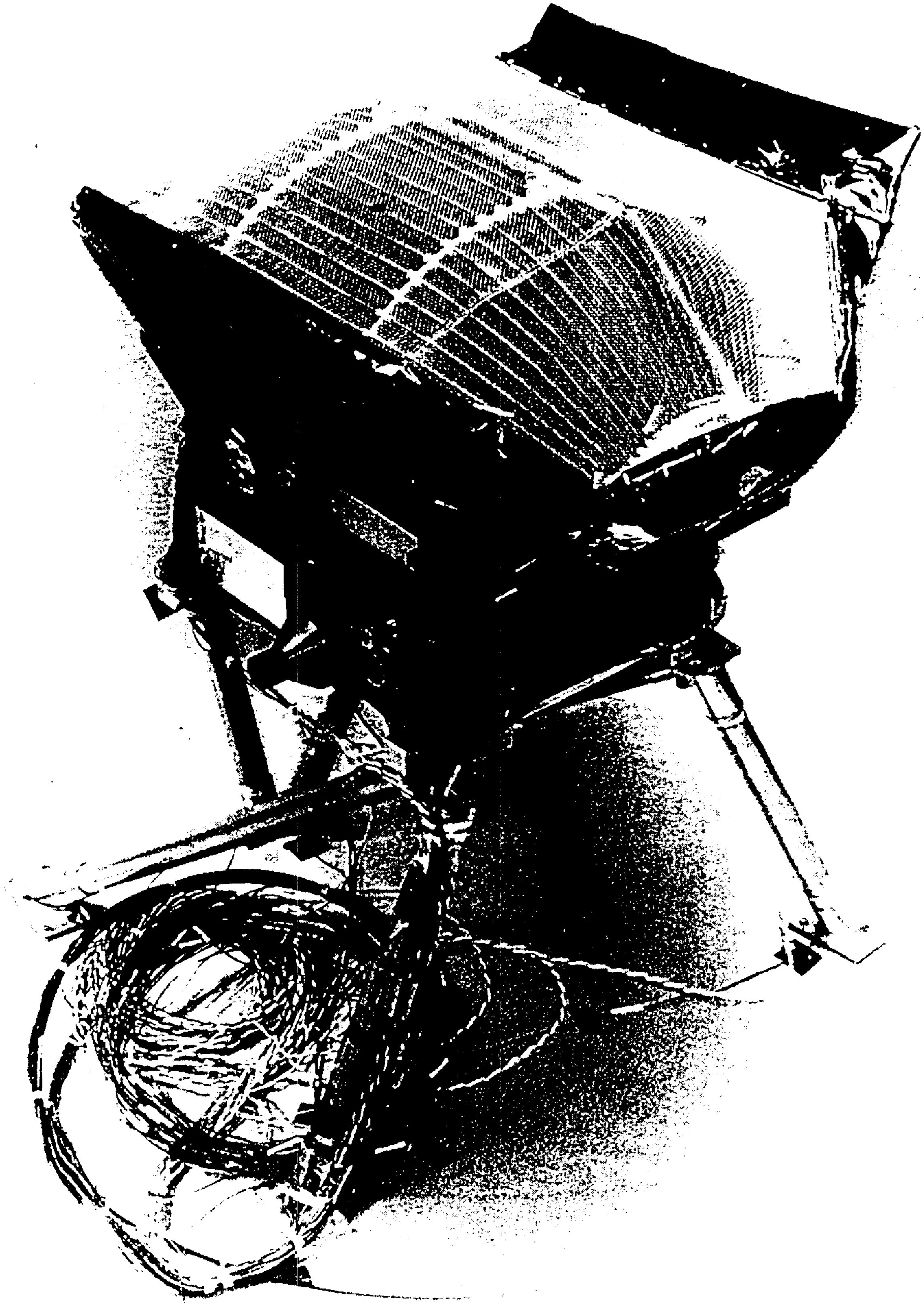


Fig. ~~12~~ 5 INCA Test Article -- View 2

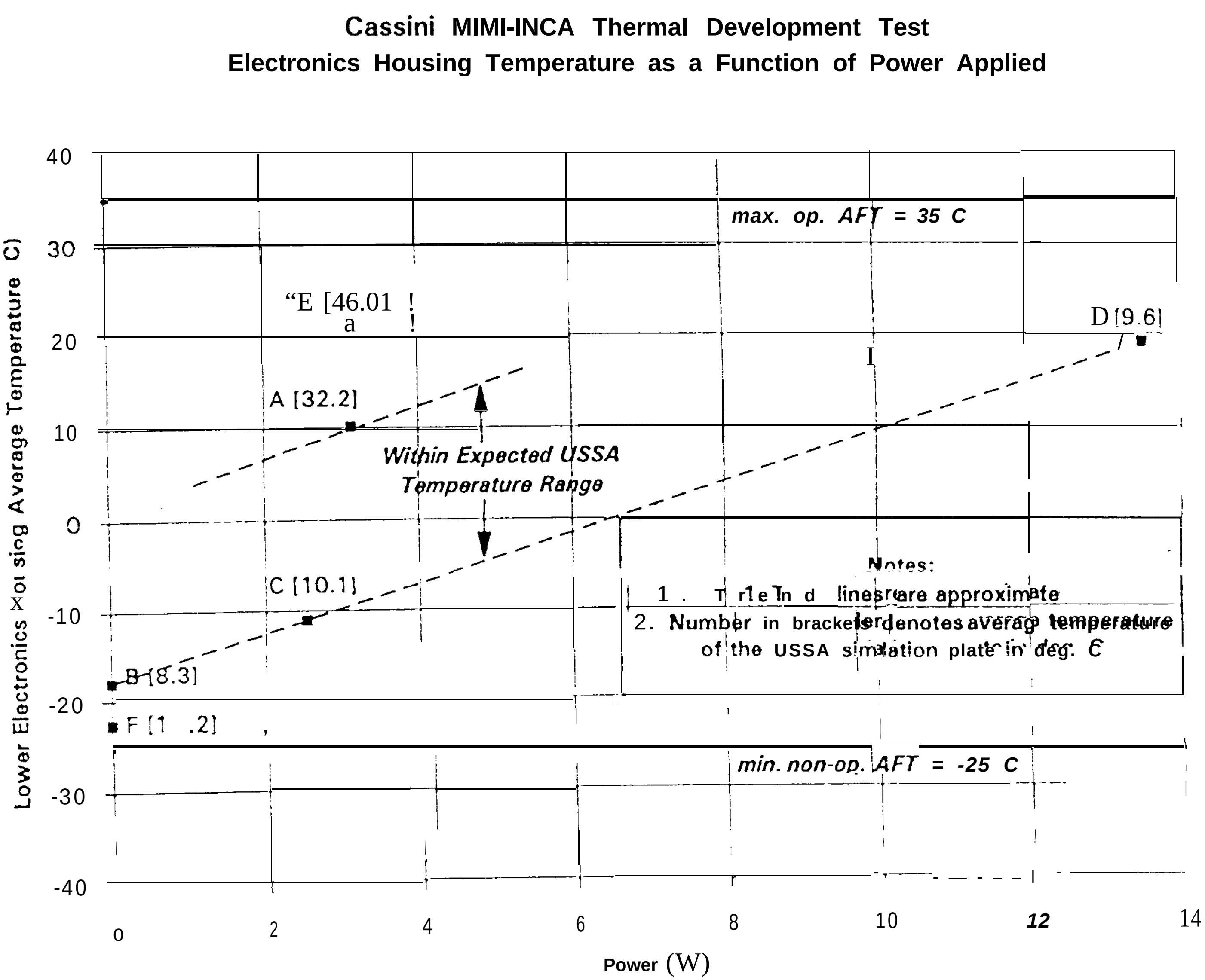


Figure ~~17~~ 6 MIMI-INCA Steady State Temperatures From Thermal Development Test

Facility Number : A2631-3 List Number : 0005

Test Name : MIMI-INCA TDT-3 List Name : APRRATURE FOIL

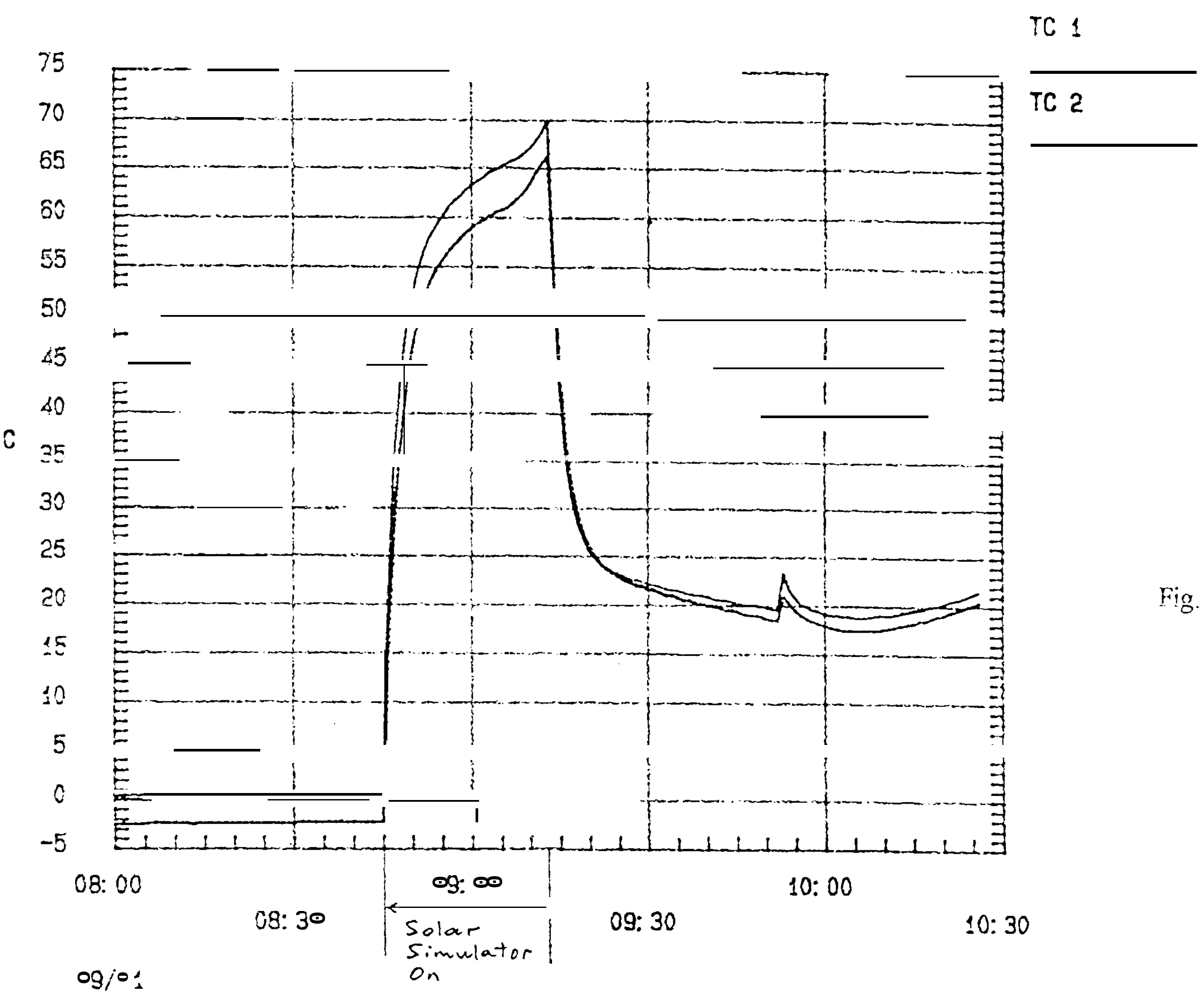


Fig. ~~23~~ 7 Aperture Foil Temperature Transients During 2.7-sun Exposure